

Quantum dot cascade laser: Arguments in favor.

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Abstract

Quantum cascade lasers are recognized as propitious candidates for future terahertz optoelectronics. Here we demonstrate several definite advantages of quantum dot cascade structures over quantum well devices, which suffer fundamental performance limitations owing to continuous carrier spectrum. The discrete spectrum of quantum dots opens an opportunity to control the non-radiative relaxation and optical loss and also provides for more flexibility in the choice of an optical and electrical design of the laser.

Key words: quantum cascade laser, quantum dot superlattice, optical cavity, multiphonon relaxation

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1. Introduction

Owing to active development in the past 10 years, nowadays quantum well cascade lasers (QW CLs) [1,2] are the most effective compact light sources in a broad range of spectrum approaching the terahertz (THz) frequencies [3,4], with practical interest from such diverse sectors as pollution and cruise control, cosmology, nanotechnology, and medicine. The performance of QW CLs, however, is fundamentally limited owing to continuous electronic spectrum in QWs, which leads to fast depletion of the upper laser level by means of LO phonon emission, as well as high optical loss and strong heating arising from free carrier absorption.

These fundamental limitations can in principle be avoided if all carriers in a cascade structure are confined in all three dimensions. That is why an idea to use quantum dots (QDs) for cascade lasing has raised

a lot of interest in recent years [5,6,7,8]. In Refs. [6,7], QDs serve mainly for reduction of nonradiative decay rate of the lasing transition. In other relations the designs of QD CLs proposed there closely resemble that of QW CL. A rather different design of QD CL, which implements a dc biased superlattice of coupled QDs, with fully discrete spectrum of carriers, was proposed in Ref. [5]. Albeit substantial technological difficulties in manufacturing the QD structures, they promise revolutionary improvement of CL characteristics [8], which was also demonstrated experimentally [9]: extremely long nonradiative lifetimes and a strong reduction of the optical loss were observed in magnetic field for a specially designed QW CL, which utilized the advantage of nearly discrete electronic spectrum at well-separated Landau levels localized by disorder. Here we present more arguments in favor of QD CLs, focusing on the opportunity to control the nonradiative relaxation in QDs and on possible novel solutions for the optical and electrical design providing a strong reduc-

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tion of the optical loss.

2. Nonradiative relaxation in quantum dots

All existing models [5,6,7,8] of QD CLs are built on the assumption of a significant reduction of the nonradiative decay rate for the lasing transition as compared to QW structures. This assumption is based on the following: (i) in QWs, intersubband transitions via optical phonon absorption are very fast and only weakly depend on the energy separation of the subbands; (ii) only phonons with wavelength $1/q \sim d$ effectively interact with electrons localized by the potential of a QD of size $d \sim 10 \text{ nm} \gg a_0$, where a_0 is the lattice constant of the host material, surrounding QD. It follows that transitions mediated by acoustic phonons are strongly suppressed for the energy separation Δ of QD levels exceeding few meV, while optical phonons with $qa_0 \ll 1$ are effectively dispersionless and thus cannot cause transitions between QD levels.

To make the relaxation in this system possible, we consider two electron states, $|1\rangle$ and $|2\rangle$, coupled to dispersionless optical phonons that have a finite lifetime due to anharmonic interaction (AHI) with all other phonon modes [10]. In absence of both AHI and Fröhlich coupling u_{12} of the two states, each QD level forms a polaron ladder, $|n\nu\rangle$, with the spectrum $E_{n\nu} = E_n + \hbar\Omega(2\nu + 1 - u_{nn}^2)/2$, where Ω is the optical phonon frequency, $n = 1, 2$, $\nu = 0, 1, 2, \dots$, and $u_{nm} \ll 1$ are Fröhlich interaction parameters. Account for the coupling u_{12} leads to mixing of the states of the two ladders. In turn, AHI makes real transitions between the polaron states possible. To lowest order in $u_{nm} \ll 1$, the rate of transition from the state $|10\rangle$ reads

$$W_{|10\rangle \rightarrow |2\nu\rangle} = |\langle 10 | \mathbf{x} | 2\nu \rangle|^2 w(\Delta_\nu). \quad (1)$$

Here $w(\Delta_\nu)$ is the probability of anharmonic decay of a virtual optical phonon accompanied by transfer of the energy $\hbar\Omega\Delta_\nu = E_1 - E_2 - \nu\hbar\Omega$ to the phonon bath. The square of the matrix element of the optical-phonon displacement operator \mathbf{x} is given by [12]

$$\langle 10 | \mathbf{x} | 2\nu \rangle^2 = \frac{u_{12}^2(u_{11} - u_{22})^{2\nu}}{2^{\nu-1}\nu!(\Delta_\nu^2 - 1)^2} \left(1 + \frac{\nu}{\Delta_\nu}\right)^2. \quad (2)$$

Equations (1), (2) demonstrate a strong dependence of the nonradiative relaxation rate on the energy separation $\Delta = E_1 - E_2$ of the QD levels. In the vicinity of the resonances $|\Delta_\nu| \sim 0, 1$ one should additionally

take into account the avoided crossing of the mixed polaronic levels. In particular, the width of the resonance at $\Delta \sim \hbar\Omega$ is of order $\hbar\Omega|u_{12}|$. Correspondingly, near the resonance with the optical phonons the relaxation rate $W_{|10\rangle \rightarrow |20\rangle} \sim w(1)$ is approximately the decay rate of the optical phonon in the host crystal, $W_{|10\rangle \rightarrow |20\rangle} \sim w(1) \lesssim 10^{12} \text{ s}^{-1}$. By contrast, for the energy separation $\Delta \sim 2.5\hbar\Omega$, which we use in the following for the laser transition energy, Eqs. (1), (2) give few orders of magnitude smaller rate, $W(2.5\hbar\Omega) = W_{|10\rangle \rightarrow |22\rangle} + W_{|10\rangle \rightarrow |21\rangle} \sim u^6 w(1/2) + u^4 w(3/2)$, where we put $u_{22} \sim u_{11} \sim u_{12} \equiv u \ll 1$.

3. Minimal transport model of QD CL

Here we outline the operation principle of a "two-level" scheme of QD CL [8], as illustrated in Fig. 1. The active media of the QD CL utilize chains of coupled QDs [13] subjected to a strong dc field, which provides a resonance between the ground state in every QD with the excited state of the neighboring dot (dashed lines in Fig. 1). Large tunneling coupling between the resonant states leads to strong mixing and splitting. The separation of the splitted levels is adjusted by applied voltage to the resonance with optical phonons, $E_{12} \simeq \hbar\Omega$, providing high transition rate $\gamma \sim 10^{12} \text{ s}^{-1}$ between them. By contrast, scattering time τ between lasing levels 1 and $2'$, separated by $\hbar\omega = 2.5\hbar\Omega$, is large, say, $\tau = 100 \text{ ps}$ (see previous section). In dynamic equilibrium, the total occupancy of a dot $n = n_1 + n_2$ is constant along the chain, while the splitted levels at each stage of the cascade are nearly in thermal equilibrium: $n_2(1 - n_1) = \exp(-\hbar\Omega/T)n_1(1 - n_2)$. As a result, population inversion $\delta = n_1 - n_2$ between the lasing levels occurs:

$$\delta = \coth(\hbar\Omega/2T) - \sqrt{\coth^2(\hbar\Omega/2T) - n(2 - n)}, \quad (3)$$

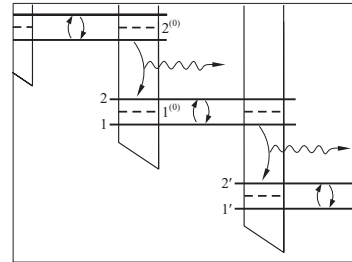


Fig. 1. Two-level scheme of QD CL.

which gives $\delta|_{n=1} = \coth(\hbar\Omega/4T) \simeq 1/3$ at $T = 300$ K, where we used $\hbar\Omega = 36$ meV (GaAs).

The current through the chain, $J = en_1(1 - n_2)/\tau$, is

$$J = (e\delta/\tau) [1 - \exp(-\hbar\Omega/T)]^{-1}. \quad (4)$$

It is important to mention that, unlike QW superlattices [14], in QD CLs the applied voltage can be adjusted in such a way that the inverse population occurs on the rising branch of the static current-voltage characteristics, thus ensuring the electrical stability of the laser operation.

4. Optical/electrical design

In QW CLs, both the electrical component of the laser mode and direction of injection current should be perpendicular to the QW planes. Thus, only TM modes of the cavity can be used. Further, the whole interior of the cavity should be heavily doped to enable the current densities $\sim \text{kA}/\text{cm}^2$, which results in a high optical loss and strong heating effects. By contrast, in QD structures the oscillator strength for the optical transition is nearly independent on the field orientation, while the free-carrier optical loss of QW CLs is absent.

The sketch of an optical/electrical design that benefits from the above advantages of QD structures is illustrated in Fig. 2. Parallel chains of coupled QDs, oriented along the y direction, form a lateral QD array in the plane $x = 0$, where the electric field $E_y(x)$ of the lowest TE mode of the cavity has a maximum. The optical confinement is provided by the dielectric profile in the x direction. Side metal contacts at $|y| > w/2$ provide current injection and operation voltage across the chains, and confine the TE mode in the y direction. Inside the cavity, the optical loss is negligible, as the

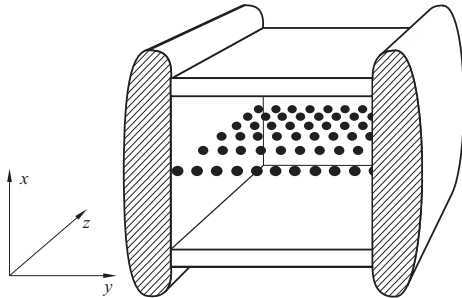


Fig. 2. Design of the “planar” QD CL

whole structure surrounding QDs is dielectric, so that optical absorption in the metal near the interfaces becomes the main source of loss. For a good metal with the surface impedance ζ , the optical loss, which is associated with the Foucault currents induced by the magnetic components H_x and H_z , is $\beta_{Mt} \simeq \text{Re} \zeta/w$. Using the Drude approximation for the specific case of palladium contacts, the laser frequency $\hbar\omega = 2.5\hbar\Omega = 90$ meV, and the stripe width $w = 5\mu\text{m}$, we get the T -independent optical loss $\beta_{Mt} \sim 1 \text{ cm}^{-1}$, which is much lower than usual internal loss in QW CLs.

We conclude with an estimation of the laser characteristics at the generation threshold, where the peak modal gain become equal to the total loss:

$$\Gamma_{\text{th}} = 16\pi\alpha |r|^2 a d Q \delta_{th} / \lambda = \beta_{Mt} + \beta_m. \quad (5)$$

For the estimate of the threshold inversion δ_{th} we take the quality factor of the laser transition $Q = 50$, the dipole matrix element of the transition $r = 2$ nm, the QD chain period $d = 10$ nm, the distance between the chains $a = 20$ nm, and the mirror loss $\beta_m = 2 \text{ cm}^{-1}$. Using $\alpha = 1/137$ and the operation wavelength $\lambda = 14 \mu\text{m}$, we get $\delta_{th} \sim 0.1$, which is several times smaller than the achievable value at $T = 300\text{K}$, see Eq. (3). According to Eq. (4), $\delta_{th} = 0.1$ corresponds to the threshold current $J_{th} \sim 0.1$ nA per chain, i.e., to the threshold current density (averaged over the contact area) $j_{th} = J_{th} 4\sqrt{\epsilon}/a\lambda \sim 0.5 \text{ A}/\text{cm}^2$. This value is at least two orders of magnitude smaller than the threshold current density of QW CLs at $T = 300\text{K}$.

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